

Figure 1509. Sandia Mountains (U.S.N.M. no. 855). Coarsest octahedrite of group IIB. The Widmanstätten pattern, although coarse, is obvious. Skeleton schreibersite crystals are common (S). Deepetched. Scale bar 30 mm. S.I. neg. 33685B.

dense tangles of subparallel lines near schreibersite, otherwise they are normally developed. Neumann bands are common; they are up to  $10\,\mu$  wide in clear kamacite with large rhabdites, but only about  $1\,\mu$  wide in kamacite with dense clouds of 0.5-1  $\mu$  rhabdite precipitates. This suggests that the major precipitation had taken place when the Neumann band-forming event took place – that is, the mass was at least below some  $300^{\circ}$  C. Later a gentle annealing has partially eliminated many of the Neumann bands; they are faintly decorated with < 0.5  $\mu$  precipitates, and they are interrupted in places, giving way to tangles of subboundaries. The microhardness is  $210\pm10$ .

Taenite and plessite are very scarce, occurring only with one 0.2-0.4 mm field per 10 cm<sup>2</sup>. One particular field, in a grain boundary, consisted of taenite with scattered, 1  $\mu$ wide kamacite needles in the interior. The martensitic transition zone had a hardness of 380, while the interior had a hardness of 295. The taenite rim itself was too narrow for measuring.

Schreibersite is common as  $25 \times .3$  or  $10 \times 1$  mm skeleton crystals and as 0.1 mm wide grain boundary veinlets. In several places schreibersite, kamacite and troilite form pockets, e.g.,  $3 \times 2 \times 1$  cm in size, of what appears to be coarse eutectic structures. They are similar to structures observed in Summit, São Julião and other irons of group IIB, but perhaps less frequent. The schreibersite is monocrystalline and has a microhardness of 900±25. In a zone, 2-5 mm wide, around the schreibersite only very small rhabdites, 0.5-1  $\mu$  across, have precipitated. Farther away, the rhabdites attain cross sections of 5-15  $\mu$ , sometimes occurring as branched units. By point counting of sections totaling 485 cm<sup>2</sup>, the bulk phosphorus content was estimated to be 0.40%, in reasonable agreement with the average of the two published, analytical values.

Troilite occurs as 1-10 mm nodules and elongated bodies, particularly as the central part of clusters of schreibersite crystals. The troilite is monocrystalline and contains about 10% daubreelite as angular blocks and lamellae. Chromite is present as rather large euhedral crystals. In one place three cubic crystals, from 4-6 mm in size, were associated with a coarse troilite-schreibersite-metal eutectic.

Cohenite, another accessory mineral, covers the large schreibersite crystals with discontinuous,  $5-150 \mu$  thick rims.

Sandia Mountains is structurally related to El Burro, Ainsworth, Iredell, and Mount Joy and is a typical member of group IIB. See also New Mexico.

Specimens in the U.S. National Museum in Washington:

1,190 g slice (no. 855, 16 x 10 x 1.3 cm)

30 g fragments (no. 855)

40 g hammered, detached kamacite grain (no. 2292, 2 x 2 x 1.5 cm)

412 g part slice (no. 2292, 13 x 6 x 0.8 cm)

Sandtown, Arkansas, U.S.A.
35°56'N, 91°38'W; 150 m

Medium octahedrite, Om. Bandwidth 1.20 $\pm$ 0.20 mm. Annealed, duplex  $\alpha + \gamma$ . HV 200 $\pm$ 8.

Group IIIA. 8.09% Ni, about 0.2% P, 21.0 ppm Ga, 41.4 ppm Ge, 1.4 ppm Ir.

Originally listed as Joe Wright Mountain No. 2.

#### HISTORY

A mass of 9.4 kg was found in 1938 in Independence County, the same county in which Joe Wright Mountain was found in 1884. Therefore, it was tacitly assumed that it was a second fragment of Joe Wright Mountain, and it was listed as such (Nichols 1939; Horback & Olsen 1965: 239; Hey 1966: 222). Inasmuch as the new locality – Section 21, Township 15N, Range 6W – places the find about 20 km northwest of the original find, I suggested to Dr. E. Olsen of the Field Museum that the 9.4 kg mass be cut in order to test my hypothesis that the two irons were different. The present examination confirms that the two masses are independent falls. They have different structures



Figure 1510. Sandtown (Chicago no. 2265). Degenerated comb plessite and annealed, duplex kamacite. Etched. Scale bar  $300 \mu$ .

and chemical composition, and they are probably of different terrestrial age. The "new" meteorite will be called Sandtown after a small community, three kilometers south of the place of find, and 15 km north of Batesville.

#### COLLECTIONS

Chicago (9.2 kg main mass), Copenhagen (105 g), Washington (100 g).

### DESCRIPTION

The meteorite is a rather flat slab, measuring  $21 \times 18 \times 6$  cm. Fine, yellow sand is still adhering to it in places. Although at first glance it appears much weathered, a closer inspection shows the fusion crust to be present in numerous places. It is estimated that less than 0.5 mm is lost by corrosion, on the average. Regmaglypts are few and shallow, and the two almost flat opposite sides represent a front and a rear side, respectively, during a stabilized atmospheric penetration.

The two slices that were cut through one end provided material for comparison of the front and the rear sides. The heat-affected  $\alpha_2$  zone is 1-4 mm thick, reaching its maximum under the rear side where the ablation rate was lowest and at times negative. The ablation-melted metal from the front side has spilled over onto the rear side and in numerous places indented it, creating pockets of fused metal, 3-6 mm wide and 1-2 mm deep. The fused metal has solidified in concentric whirlpool structures, formed by the air current eddies, and incorporates tiny magnetite spherules, 5-50  $\mu$  in diameter, which are sometimes hollow. The metal itself is columnar and dendritic with 5-25  $\mu$  wide cells and 2-3  $\mu$  dendritic armspacing. The microhardness is 280±30. The heat alteration zone, which normally is a plain  $\alpha_2$  structure, is highly anomalous here because it was formed from a fine-grained, duplex  $\alpha + \gamma$  matrix. Its hardness is 190±10. The hardness passes a minimum of 165 at the 700° C isotherm, and then increases to the unaffected interior level of 200±8 (hardness curve type II).

The etched sections display a medium Widmanstätten structure with an indistinctly oriented sheen. The kamacite lamellae are slightly undulating, long ( $\frac{L}{W} \sim 20$ ) and have a width of 1.20±0.20 mm. No Neumann bands can be distinguished at low magnification; only a slightly striated matrix which appears to be loaded with precipitates can be observed. With a 40x oil immersion objective, the matrix resolves to a very fine-grained duplex  $\alpha + \gamma$  structure. The individual  $\gamma$ -particles are about 0.5  $\mu$  across and densely spaced; they are often aligned according to some previously existing shear planes in the  $\alpha$ -phase – which indicate a previous  $\epsilon$ -structure. Some 5-15  $\mu$  wide zones around the schreibersite crystals are free of precipitates - presumably because the nickel concentration here was too low for supersaturation to occur - and this narrow zone shows finely recrystallized kamacite. The structure appears to be the result of a longtime annealing, and in some respects it resembles the structure of Dalton, Plymouth and Cratheus (1931). The microhardness is 200±8.

Taenite and plessite cover 25-30% by area, both as comb and net plessite and as dark-etching "black taenite." The interior of all plessite fields is decomposed to relatively soft (~300) duplex  $\alpha + \gamma$  mixtures, similar to that of the kamacite lamellae but in a wide range of sizes. The numerous submicroscopic precipitates in the high-nickel taenite are interesting. They appear to have decorated



Figure 1511. Sandtown (Copenhagen no. 1970, 223). Fissured schreibersite crystal and annealed kamacite. Etched. Oil immersion. Scale bar 20  $\mu$ .



Figure 1512. Sandtown. Detail of Figure 1511. The kamacite is recrystallized and decomposed. A large number of fine  $\gamma$ -particles occur everywhere. Etched. Oil immersion. Scale bar 10  $\mu$ .

SANDTOWN – SELECTED CHEMICAL ANALYSES

	pe	rcentage						ppm				
Reference	Ni	Со	Р	С	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Scott et al. 1973	8.09								21.0	41.4	1.4	

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densely spaced slipplanes that form a grid of 2-3 directions, with only  $0.4-2\mu$  between consecutive parallel planes. Similar planes, decorated by submicroscopic particles, were noted in, e.g., Anoka, Grant and Plymouth, but a closer examination probably requires electron microscopic techniques. The hardness of the annealed grid taenite is  $225\pm20$ .

Schreibersite was not observed as large crystals, but it is common as 20-100  $\mu$  wide grain boundary veinlets and as 5-25  $\mu$  vermicular bodies inside the plessite. It is monocrystalline but somewhat shattered. Rhabdites are not present. The bulk phosphorus content is estimated to be about 0.2%. Chromite was noted in one place in the kamacite as a 0.6 mm euhedric crystal. Its hardness was 1130±50, and it had acted as a nucleating substrate for a discontinuous, 50  $\mu$  wide rim of schreibersite.

Troilite and other minerals were not present in the small sections.

Sandtown is similar to such medium octahedrites as Merceditas, Briggsdale, Dexter and Kyancutta in its primary structure. However, it must have suffered a long cosmic annealing at rather low temperatures (400° C?) in order to acquire the observed secondary structure. It is likely that the  $\epsilon$ -structure was tempered by the relaxation heat associated with a shock event. Similar annealed structures are notably present in Plymouth, Dalton, Jamestown, Karasburg, Cratheus (1931), Maria Elena and several other iron meteorites of various primary structures. With respect to its shape, Sandtown is one of those few flat meteorites, such as Arlington and Tawallah Valley, which may have been produced by scabbing from the rear of a larger mass that was violently impacted. Sandtown shows, as do Arlington, Jamestown and others, the effects of a stabilized flight through our atmosphere.

Specimen in the U.S. National Museum in Washington: 100 g slice (no. 5600, 5.5 x 4 x 0.7 cm)



Figure 1513. Sandtown (Copenhagen no. 1970, 223). From the heat-affected A zone (page 53). A schreibersite crystal is fused and the  $\gamma$ -particles of the duplex kamacite are partially resorbed. Etched. Oil immersion, Scale bar 20  $\mu$ .



**Figure 1514.** Sandtown (Chicago no. 2265). Detail of the heataffected  $\alpha_2$  zone. Decomposed plessite fields (P) and decomposed kamacite lamellae (K). Etched. Oil immersion. Scale bar 20  $\mu$ .

# San Francisco del Mezquital, Durango, Mexico 23°29'N, 104°22'W

Artificially reheated hexahedrite, H.  $\alpha_2$  matrix.

Group IIA. 5.50% Ni, 0.20% P, 61 ppm Ga, 183 ppm Ge, 21 ppm Ir. The whole mass has been artificially reheated although not recorded in the source literature.

#### HISTORY

A mass of about 7.5 kg was brought from Mexico to France in 1867 by General Castelnau. It was said to have come from San Francisco del Mezquital in the state of Durango, a place which Burkart (1870: 685) was able to identify as a town of 1430 inhabitants, commonly named Mezquital, about 70 km southeast of Durango, corresponding to the coordinates given above. Daubrée (1868b) gave a brief description of the mass and of a 175 g specimen acquired for the Paris Museum, accompanied by an analysis of Damour. Fletcher (1890a: 156) stated that a deep-etched section of 130 x 70 mm area was dull, except for several straight, parallel lines running completely across the face at intervals of one or two millimeters from each other, a feature which reminded him of Coahuila. Brezina (1896: 294) described a specimen obtained from the main mass, which had been acquired about 1870 by the British Museum and from which a few small slices had been cut for exchange. Cohen (1905) presented his own observations together with a bibliography and a new analysis. Berwerth (1914: 1079) was the first to conclude that the peculiar structure was due to artificial reheating, but his viewpoint was apparently forgotten. Perry (1944) presented three photomicrographs and compared the structures with Chesterville and, less well-chosen, to those of La Primitiva and New Baltimore. Reed (1969) found the anomalously high concentration of 0.22% P in solid solution in the kamacite, a figure which is better understood when it is

acknowledged that most of the previously existing rhabdites have now become dissolved in the matrix by an artificial heat treatment.

## COLLECTIONS

London (7,085 g main mass and 20 g pieces), Paris (150 g), Vienna (73 g), Harvard (51 g), New York (36 g), Vatican (20 g), Utrecht (15 g), Chicago (12 g). The 30 g specimen in Berlin, described and figured by Klein (1906: 129), appears to belong to some other meteorite, a damaged octahedrite.

#### DESCRIPTION

According to Daubrée (1868b) the mass had the overall dimensions of  $28 \times 13 \times 7$  cm and was remarkably flattened. The two larger faces were almost parallel and rather smooth, although certain pits and cavities might be found. He also mentioned a cylindrical hole, 5 mm in diameter. Since, as shown in the following, the whole mass must have been reheated to about 800° C, the hole may be the cavity left when a near-surface troilite nodule oxidized, melted, and sweated out.

The Harvard fragment, of 51 g, shows clear indications on the surface of hammering and, in addition, some heating. A 20 g specimen, cut from the main mass, was kindly lent me by Dr. Hey, London, for metallographical examination. The polished and etched section displays a rather homogeneous "ataxitic" structure in which scattered 0.1-1 mm nonmetallic inclusions are embedded. The parallel bands, observed by Fletcher, are also present. At higher magnification it becomes clear that all the matrix is transformed to 50-300  $\mu$  servated  $\alpha_2$  grains of random orientation, which is the reason for the lack of oriented sheen. This structure is identical to that of technological Fe-6% Ni alloys, cooled rather rapidly to room temperature from about 800° C; and it is also similar to the inner parts of the natural, heat-affected  $\alpha_2$  zone present on many iron meteorites. However, when the structure is preserved all through the material - as it apparently is here, judging from this study and from older descriptions of other pieces, (e.g., Cohen 1905; Perry 1944), - it must be concluded that the mass has been artificially reheated, although this was never mentioned in the source literature.

This conclusion is corroborated by an examination of the inclusions. Schreibersite is present as scattered 0.1-1 mm skeleton crystals, often precipitated around a

nucleus of cubic,  $100-300 \,\mu$  chromite crystals. Rhabdites were previously ubiquitous in the matrix, except near the larger phosphide crystals, as  $1-10 \mu$  prisms. And the parallel lines mentioned above are original Neumann bands which stand out markedly because they have been decorated with 5-10  $\mu$  rhabdite particles in much the same way as seen in Scottsville and some other hexahedrites. However, all rhabdites are either already dissolved or enveloped in a halo, about  $5 \mu$  wide, suggesting partial resolution in the matrix. The schreibersite, although still monocrystalline, is significantly attacked and shows scalloped edges and tiny diffuse islands in front of it, and the troilite is recrystallized to aggregates of 15-50  $\mu$  grains. The chromite appears to be unaffected. These observations may best be interpreted to indicate a short heating - about half an hour - to about 800° C. Higher temperatures would have eliminated or melted the inclusions more fully. It is interesting to note that many of the  $\alpha_2$  units contain Neumann bands, particularly near the surface. The Neumann bands are not remnants of the original population but were produced artificially, I think, when the mass was cold-hammered. Similar late Neumann bands are present in Cacaria.

The unusual photomicrographs by Perry (1944: plate 68) of a specimen in the American Museum of Natural History may hereafter be understood as showing the products of high temperature intercrystalline oxidation and



Figure 1515. San Francisco del Mezquital (New York no. 140). Artificially reheated hexahedrite. Near-surface section showing high temperature intercrystalline reaction products and an unequilibrated  $\alpha_2$  matrix. Etched. Scale bar 200  $\mu$ . (Perry 1944: plate 68.)

	percentage							ppm				
References	Ni	Со	Р	С	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Damour in Daubrée												
1868b	5.89	0.39	0.23									
Fahrenhorst in Cohen												
1905	5.46	0.87	0.16		1500		300					
Wasson 1970,												
pers. comm.	5.50								61.4	183	21	

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reactions among meteoritic minerals, limonitic minerals and the atmosphere – all being a result of artificial reheating.

San Francisco del Mezquital was probably originally a normal hexahedrite, with characteristics intermediate between Scottsville and Coahuila, but with a rather high proportion of chromite crystals. Upon reheating to about 800° C by the finders and some hammering, the mass was unfortunately transformed into a "nickel poor ataxite."

## San Francisco Mountains, Arizona, U.S.A. Approximately 35°25'N, 111°50'W; 2400 m

Fine octahedrite, Of. Bandwidth  $0.23\pm0.04$  mm. Deformed Neumann bands. HV 190±10.

Group IVA. 7.62% Ni, less than 0.05% P, 2.09 ppm Ga, 0.10 ppm Ge, 3.0 ppm Ir.

#### HISTORY

A mass of 1.65 kg was found about 1920 by a shepherd on the lower northerly slopes of the San Francisco Mountains in Coconino County. The exact locality has not been identified. The mass passed through several hands before S.H. Perry was able to locate it and purchase it in 1928. Perry described it thoroughly and gave numerous pictures of the exterior and of an etched section (1934). He donated the mass to the Smithsonian Institution in 1938, except for a 36 g specimen kept by him and later donated to Chicago. Before Perry acquired the main mass of 1,553 g, a small section of approximately 100 g had been cut from it for assaying. What remained after assaying -60 g - was relocated by Nininger (Nininger 1933a: 9; Perry 1934) and in 1959 was divided between London and (1933c: figure 9) Tempe. Nininger illustrated the heat-affected rim zone; the figure was reprinted by Nininger



Figure 1516. San Francisco Mountains. (U.S.N.M. no. 1270). Close-up of the well-preserved fusion crust. The hair-lines and the exterior layer consist of iron oxides. Smoked with NH<sub>4</sub> Cl. Scale bar approximately 1 cm. S.I. neg. 1379A.

## SAN FRANCISCO MOUNTAINS - SELECTED CHEMICAL ANALYSES

	pe					ppm						
Reference	Ni	Co	Р	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Schaudy et al. 1972	7.62		_					-	2.09	0.10	3.0	



Figure 1517. San Francisco Mountains. The same as Figure 1516 but from a different angle. Scale bar approximately 1 cm. S.I. neg. 1379.

& Nininger (1950: plate 16). Perry (1944) again discussed the microstructure and gave seven photomicrographs.

## COLLECTIONS

Washington (1,334 g), Chicago (36 g), Tempe (30 g), London (28 g).

## DESCRIPTION

The mass is one of the best preserved iron finds. Its shape may be compared to a rectangular box, which – if placed in an X-Y-Z coordinate system – possesses an (001) face, an (010) and a (100) face, while the remaining faces are obliquely cut with a (111) plane. All edges are smoothly rounded, and no regmaglypts proper are present. The average dimensions are  $10.5 \times 6 \times 6$  cm, with the longest edge lying in the X-direction. It appears that the mass was oriented during flight, with the origin as apex and the (111) plane as rear face. Along the edges of this face, a



Figure 1518. San Francisco Mountains (U.S.N.M. no. 1270). Cut and etched end of the mass. The Widmanstätten pattern is distorted. It is superimposed by a matte  $\alpha_2$  rim zone from the atmospheric flight. At F there is a thick metallic fusion crust. Deep-etched. Scale bar 10 mm, (Perry 1934: Figure 3.)

considerable amount of melted and resolidified metal has built up a bulging deposit, 1 mm thick, while the remainder of the surface has practically no metallic fusion crust. The overall shape resembles that of the hexahedrite Keen Mountain.

The surface is covered with a blue-black fusion crust, 0.1 mm thick, except where it is pealed off by slight weathering and excessive handling. "The crust is marked by striations and fine ridges, which in places resemble hairs blown thickly across the surface, crossing one another" (Perry 1934). Sections perpendicular to the surface reveal that the oxide crust is duplex, being composed of an interior layer of wüstite and an exterior one of magnetite, each 25-60  $\mu$ . Furthermore, the wüstite is decomposed partially to magnetite; this seems to have been an exsolution process in the solid state. The magnetite forms cubic skeleton crystals, 1-5  $\mu$  across, and grain boundary zones 1-10  $\mu$  wide.

The metallic part of the fusion crust ranges from 0-1 mm in thickness. The thickness is achieved by a buildup of successive sheets, each 25-100  $\mu$  thick. In one place at least 12 individual layers could be identified; they taper out irregularly, and oxidic fusion crusts are intercalated in the exterior parts. The metal is solidified to dendritic-columnar grains which have grown more or less perpendicular upon the substrate, with an average thickness of  $5-10 \mu$ . It has transformed to  $\alpha_2$  and has a hardness of  $340\pm40$ . The metal has dispersed oxide globules,  $0.5-30 \mu$  across, and — particularly in the outer layers — it appears that there are many interdendritic cavities and gasholes.

Under the fusion crust there is a beautiful, heat-affected  $\alpha_2$  zone which ranges in thickness from 2-6 mm. Greater thicknesses are found locally but are the result of taper sectioning through curved parts of the surface. The lower thickness of 2 mm is present under what is believed to have been the apex and adjacent parts of the leading surface in flight, while the higher thickness is found under the millimeter-thick metal deposits. This is in



Figure 1519. San Francisco Mountains (Tempe no. 138ax). Coldworked kamacite with distorted Neumann bands and wedge-shaped deformation bands. Patches of recrystallized grains. Etched. Scale bar 400  $\mu$ .

# Santa Apolonia, Tlaxcala, Mexico 19°14'N, 98°19'W

Medium octahedrite, Om. Bandwidth 0.95 $\pm$ 0.10 mm.  $\epsilon$ -structure. HV 303 $\pm$ 20.

Group IIIA. 7.54% Ni, 0.50% Co, 0.12% P, 19.5 ppm Ga, 35.8 ppm Ge, 8.3 ppm Ir.

## HISTORY

A mass of 1,050 kg was found in 1872 near the pueblo of Nativitas, in the State of Tlaxcala and was – probably shortly after 1900 – transferred to the Institute of Geology, Mexico City, where Ward noted it. He acquired about a pound and kept half for his collection (Ward 1904a: 22), while he exchanged the balance (Klein 1906: 22, 136). Haro (1931: 78, 81 and plate 35) briefly mentioned the pieces in Mexico City and gave a rough picture of one of them. Furthermore, Haro's Plate 36, appears to give a full view of the mass; the picture certainly does not represent Durango, although so stated in the text.



Figure 1522. Santa Apolonia. The main mass as exhibited in the entrance hall of the Institute of Geology, R. Cipres No. 176, Mexico City. The triangular slab measures approximately 93 x 93 x 33 cm.

The iridium value by Hawley (1939) includes all platinum metals. Nininger (1931c) reported lawrencite; the iron Nininger visited the institute in 1929 and was allowed to examine an 85-pound specimen broken from the main mass; he described the meteorite thoroughly (1931c) with photographs of the exterior, of an etched slice and of small octahedral fragments detached from the meteorite by terrestrial weathering. According to Nininger, it was small fragments of this character which were first discovered by prospectors among gravel in a gully. Upon further investigation the main mass was located farther up the slope of the mountain. Nininger proposed the name Nativitas but also used the name Tlaxcala (1933a). Although he questioned the authenticity of Ward's material and observations, there seems to be no doubt that Ward's 212 g specimen (now in Chicago) is authentic and that Ward's information as to the main mass is correct. Therefore, there is little reason to abandon the original name of Santa Apolonia which serves well to identify the material. There are numerous villages by the name Nativitas in Mexico; the one associated with the meteorite appears to lie about 15 km southwest of the town of Tlaxcala and has the coordinates given above.

Jaeger & Lipschutz (1967b) estimated a shock pressure of 400-750 k bar. Wood (1964) showed electron microprobe profiles across various plessite fields, and Reed (1969) found the kamacite to contain 7.3% Ni and 0.10% P in solid solution. Schultz & Hintenberger (1967) determined the occluded noble gases. The cosmic ray exposure age was estimated to be  $840\pm410$  million years by the <sup>21</sup>Ne/<sup>26</sup>Al method (Lipschutz et al. 1965), and 730\pm65 million years by the <sup>40</sup>K/<sup>41</sup>K method (Voshage 1967).

## COLLECTIONS

Instituto Geologico, Mexico City (No. 80: main mass of about 1,050 kg; No. 46: two weathered specimens totaling 1,050 g; No. 50: 117 g limonite); Tempe (8.8 kg), Washington (5.7 kg), London (3.65 kg), Harvard (3.38 kg), Ann Arbor (906 g), Amherst (778 g), New York (379 g), Los Angeles (369 g), Chicago (219 g), Berlin (130 g), Vatican (88 g),

### DESCRIPTION

The main mass in Mexico City is a somewhat flattened, triangular slab measuring  $93 \times 93 \times 33$  cm. The attached

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chloride is, however, probably mainly a result of prolonged exposure to terrestrial ground water.

	percentage			_				ppm				
References	Ni	Со	Р	С	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Hawley in Nininger												
1931c	7.39	0.51	0.15	200	1300	1100	600					
Hawley 1939	7.39										12.3	
Goldberg et al. 1951	7.83								20.8			
Moore et al. 1969	7.39	0.50	0.10	240	90							
Scott et al. 1973	7.52								19.5	35.8	8.3	

label gives the weight as 1,050 kg; and even if this should not be based on actual weighing, it comes pretty close to the real weight as far as I can estimate from my examination of the mass. Nininger (1931c) estimated the weight to be somewhat higher, 1,315.6 kg (sic !). The mass is weathered, and exfoliation along the Widmanstätten planes is common. No fusion crust and no heat-affected rim zones could be identified. The mass exhibits as observed on my examination in 1968, a full, weathered surface and very little has been cut from it. Only two small, cut faces, each  $5 \times 10$  cm in size, can be seen. It appears that all distributed material comes from the 85-pound specimen which – as Nininger observed – had been separated naturally from the main mass by oxidation.

Etched sections display a medium Widmanstätten structure of straight, long ( $\frac{U}{W} \sim 35$ ) kamacite lamellae with a width of 0.95±0.10 mm. The kamacite has subboundaries decorated with 1-2  $\mu$  rhabdites, and it is transformed by shock to the typical crosshatched  $\epsilon$ -structure. Its hardness is 303±20.

Taenite and plessite cover 30-35% by area, mostly as open-meshed, degenerated comb and net plessite with discontinuous taenite frames. Many fields are nothing else but granulated kamacite cells with a few scattered taenite blebs. The three-dimensional shape of the fields becomes abundantly clear in this meteorite because many of the fields have become completely isolated – by corrosion – from the adjacent kamacite lamellae. The 'typical octahedrons and truncated octahedrons are well illustrated by Nininger (1931c: figures 3 and 4; 1952a: plate 34). A small proportion of dark-etching duplex plessite occurs at the center of the small taenite wedges (HV 330±20). The martensitic transition zones have a hardness of  $415\pm15$ . The common, easily resolvable comb plessite fields have hardnesses and structures equal to the adjacent kamacite.

Schreibersite is present as  $2-10 \mu$  wide grain boundary precipitates and as irregular, minute blebs inside the fields. Rhabdites are common, but they are small – less than  $2 \mu$  across. They are even present within the plessite fields.

Troilite occurs as nodules, 3-20 mm in size, and as rhombic bodies, typically 0.5-1 mm across. It is also present as lenticular bodies,  $3 \times 1$  mm, and occasionally as thin lamellae,  $5 \times 0.2$  mm in size. The troilite is monocrystalline with sharp boundaries against the metal – except where this is corroded, – and it contains 5-15% of daubreelite in the form of parallel lamellae. The nodules have almost no schreibersite precipitates due to the low bulk phosphorus content of the meteorite but show well developed rims of swathing kamacite, 0.5-1.5 mm wide. The small blebs are frequently composed of very thin (0.2-1  $\mu$ ) alternating lamellae of troilite and daubreelite. In addition, daubreelite is not uncommon as 10-50  $\mu$  blebs in the kamacite.

Corrosion has created centimeter-thick crusts locally. Sections through the crust reveal that the minute rhabdites and the 2-10  $\mu$  wide taenite ribbons survive almost unaltered long after all other structural elements have disappeared.

Santa Apolonia is a shock-hardened medium octahedrite of group IIIA which is related to, e.g., Canyon City, Angelica, San Angelo and Russel Gulch.

#### Specimens in the U.S. National Museum in Washington:

- 3.4 kg thick, irregular slice and fragments (no. 906, 17 x 7 x 7 cm)
- 39 g polished section (no. 2293, 4 x 1.5 x 1 cm)
- 39 g octahedral plessite fragments (no. 2293, each 2-10 mm across)
- 23 g massive limonite crust (no. 3041, 3.5 x 2 x 1 cm)

# Santa Catharina, Santa Catarina, Brazil 26°19'S, 48°39'W; 5-50 m

Anomalous troilite-rich, polycrystalline, nickel-rich iron. Heterogenous taenite. HV 175-560.

Anomalous. 35.3% Ni, 0.6% Co, 0.2% P, 1.8% S, 5.4 ppm Ga, 9.6 ppm Ge, 0.020 ppm Ir.

#### HISTORY

Several weathered masses, the largest weighing 2,557 kg, were found in 1875 by M. Goncalves da Rosa 2 km from the coast on the island of São Francisco. The best description of the circumstances of finding was given by Gonzaga de Campos in an appendix to Derby (1888). The accompanying map sketches showed the locality to be 4.2 km south-southeast of the town São Francisco do Sul on the slope of a small hill. The largest block was found at an altitude of 6 m, partly covered with soil. Many other fragments, ranging from 1,500 kg to a few kilograms were discovered within a narrow sector 230 m long and 80 m wide. The area had its apex at the hill top (58 m) and became widest at the foot of the hill. The distribution suggests that only one mass landed originally and that it burst by impact and/or was decomposed by corrosion, after which the individual fragments were slowly dispersed by gravity forces during a long terrestrial exposure.

Some of the specimens were found on the surface while others were discovered after trenches had been excavated. Lunay (1877) mentioned 14 different localities within the area, the lowest of which provided, in addition to the largest mass, two fragments of 300 kg each. A fourth, also rather metallic fragment, weighed 450 kg. However, some masses of 1,500 and 375 kg were altered extensively. Lunay estimated that a total of 7,000 kg had been recovered, while another, less reliable, estimate reported a total of 25,000 kg. (Guignet 1877). Both Lunay and Wülfing (1897: 308) stated that all masses had been sent to Europe (England) to be smelted for nickel. This has never been confirmed and appears exaggerated. Daubrée (1877b) thus mentioned only 500 kg which had been received in Europe in a much weathered, almost pulverized, state. The largest of all discovered masses is still (?)

<sup>2.2</sup> kg (no. 845)



Figure 1523. Santa Catharina (Brit. Mus. no. 52283). A severely weathered anomalous nickel-rich iron. Numerous limonite-filled cracks apparently follow a cubic pattern. Oxidized metallic patches (gray) and oxidized troilite and schreibersite inclusions (black). Polished. Scale bar 3 mm.

exhibited in Rio de Janeiro (Oliveira 1931: 36: 2,557 kg) but has never been described.

Since the meteorite is heavily weathered and very anomalous in composition and structure, it was suggested at an early date that the masses were of terrestrial origin and similar to the much disputed Ovifak masses which had been reported and discussed by Nordenskjöld (1870b) and Steenstrup (1875). Brezina (1885: 221; 1896: 234, 296) and numerous other authorities did not accept the meteoritic origin, but Derby (1888; 1892a, b) argued convincingly for it and also showed that the geological settings were widely different between Ovifak and Santa Catharina. The first had been found close to diabase dikes on an island rich in basalt and carbonaceous shales, while the latter was found in argillaceous soil capping a weathered, coarse-grained, tourmaline-bearing granite with no basaltic dikes present in the immediate vicinity of the find. The abundant presence of troilite and schreibersite, not known in terrestrial rocks, also indicated a cosmic origin. Indeed, Santa Catharina may be seen as the natural extension of the strain of other well known meteorites, particularly with Twin City as a connecting link to the low-nickel irons. Prior's catalogs (1923 and following editions) have all accepted Santa Catharina as an authentic meteorite, and today hardly anybody doubts the meteoritic origin.

Damour (1877) and Daubrée (1877a, b) analyzed and described some large specimens, and Meunier (1884: 102, 501; 1893a) added several observations and gave two excellent figures of the slices in Paris. Perry (1944: plate 33) gave four photomicrographs, and Buddhue (1950: 121) discussed briefly the oxidation products. On basis of the specimens in Copenhagen, Buchwald & Munck (1965: 18, 57) questioned the high-nickel content. We later learned that our specimens, received in 1926 from Paris, were mislabeled fragments of an oxidized, coarse octahedrite. Recently, I have found more of this same Toluca-like material, mislabeled Santa Catharina, in the Smithsonian Institution. It was mentioned, without comment, by Merrill (1916a: 194), and it can be traced back to 1884 when it was in Shepard's collection. Exactly how this misunderstanding occurred originally is difficult to understand. Since more material of the same kind may be around in various collections, I find it appropriate to issue a warning here.

Lovering & Parry (1962) included Santa Catharina in their study of the thermomagnetic properties. In order to explain their anomalous data, they assumed that two different taenite phases and a plessite phase with 55, 28 and 24% Ni, respectively, were present. Lovering & Andersen (1965), in an extension of this work, proved that part of the anomalous data might better be accounted for by the advanced oxidation: 8% oxygen was found by the electron microprobe in apparently fully metallic areas. They still maintained, however, that two different taenite phases were present, with 31.8 and 45.2% Ni, respectively, and the latter being heavily oxidized. Kvasha et al. (1969) examined a weathered specimen by X-ray diffraction and showed that the fissures followed cubic cleavage planes in the taenite. They identified only one taenite phase, with a lattice parameter of 3.581 kX. They assumed this phase to contain more nickel than their standard (40.8% Ni, 57.8% Fe, 0.5% P). But their conclusion appears to be uncertain since they compared an oxidized, copper-rich taenite with a phosphorus-rich standard, and oxygen, copper and phosphorus must influence the parameters so much that a detailed comparison cannot be made. In any case, if they accept that the major phase contains more than 40.8% Ni and also accept 34-36% Ni as the average composition for the meteorite, - there remains for them to identify a corresponding nickel-poor phase. Kamacite is certainly not present in a sufficient quantity.

Marchese et al. (1966c) examined the crust of a 28 g fragment and believed they had identified a 2-3 mm wide heat-affected rim zone. However, their arguments are not convincing, and the zone in question appears to be the hard unoxidized zone present along many internal grain boundaries, as discussed below. An estimated cosmic ray exposure age of 140 million years was given by Schaeffer & Fisher (1960) and Fisher & Schaeffer (1960), based upon noble gas determinations. Herr et al. (19(1) examined the osmium-rhenium abundances, while Starik et al. (1960) included Santa Catharina in their studies of the isotopic composition of lead.

## COLLECTIONS

Rio de Janeiro (2,557 kg), Paris (54.2 kg on 19 specimens), Chicago (42 kg on 14 specimens), Washington (800 g metal and 10 kg limonite), London (6.1 kg), Moscow (4.1 kg), Harvard (2.4 kg), Budapest (1,875 g), New York (1,500 g), Tempe (1,100 g), Ann Arbor (107 g metal, 915 g limonite), Vatican (950 g), St. Louis (556 g), Yale (515 g), Philadelphia (500 g), Bonn (468 g), Copenhagen (294 g), Calcutta (287 g), Sydney (261 g), Prague (182 g), Stockholm (178 g), Odessa (61 g), Rome (49 g), Dorpat (48 g).

#### DESCRIPTION

The largest mass, of 2.56 tons, measured 1 x 0.8 x 0.5 m. Numerous other fragments were found, ranging in size down to 10-20 cm in diameter (Derby, 1888: 27). All specimens examined by the author were weathered to a degree that resembles what is seen in Ider, Nashville, Smithville and Wolf Creek. Some specimens are nothing else than solid limonite, and others contain a metallic core 10-25 cm across inside a 10-15 mm thick crust of terrestrial oxides. Even the metallic cores are severely corroded, the corrosion following a system of crisscrossing fissures which are crystallographically determined. Kvasha et al. (1969: figures 2 and 3) have shown how the weathering splits the material along cubic planes which may be observed as regular steps on the fragmented surfaces. Under these circumstances it is not surprising that no fusion crust and no heat-affected zones may be identified; they are long since lost by weathering.

Polished sections through the metallic cores reveal an ataxitic structure with no trace of Widmanstätten precipitation, even at high magnification. In this respect, it



Figure 1524. Santa Catharina. Detail of the oxidized metal in Figure 1523. The corroded material occurs in platelets that are arranged parallel to cubic planes of the parent crystal. Those parallel to the plane of section appear as irregular gray flakes. Lightly etched. Scale bar  $30 \mu$ .

differs from Twin City which at a 5% lower nickel level exhibits the first, fine microscopic  $\alpha$ -spindles in a Widmanstätten pattern. On sections of Santa Catharina which are large enough - above about 10 cm - it may be observed that the meteorite is polycrystalline, since it is composed of austenite individuals ranging from 2-8 cm in size. The grains are separated by smoothly curved troilite veins that pinch and swell irregularly - being 1 mm wide here; increasing to 3 x 2 cm fillings of interstices between the metal in other places. Although few sections display more than 5-6 grains or parts of grains, it appears that they are randomly oriented and not, for example, individual branches on a superdendrite. The orientation of the grains is not easily detected, since no Widmanstätten precipitates occur. The orientation may be examined by X-ray techniques but may also be roughly estimated from the sliplines created by a hardness impression and from the shape of the hardness impression itself. The orientation may also be deduced by noting the natural corrosion along preexisting slipplanes or by noting the oxide-filled fractures which mainly follow cubic planes. The morphology of randomly oriented metal grains - separated by substantial amounts of troilite - resembles the morphology of San Cristobal, Soroti, Pitts and Persimmon Creek. A similar morphology with less prominent troilite is present in Twin City, N'Goureyma and others.



Figure 1525. Santa Catharina (Harvard no. 360). Oxidized zones alternate with unoxidized. Lightly etched. Scale bar 100  $\mu$ . (Perry 1944: plate 33.)

	percentage							ppm				
References	Ni	Co	P	С	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Dyakonova &												
Charitonova 1963	33.69	0.66	0.19				1400					
Cobb 1967	38.5	0.53					1500				<1	
Smales et al. 1967						<5	850	3	5.4	10.2		
Wasson & Schaudy												
1971	33.62								5.3	9.1	0.020	
Crocket 1972											0.049	<0.5

SANTA CATHARINA - SELECTED CHEMICAL ANALYSES



Figure 1526. Santa Catharina (Brit. Mus. no. 52283). A silicate crystal (black) upon which a schreibersite crystal has nucleated and grown. In addition, terrestrial limonite along the schreibersite taenite interface. Polished. Scale bar  $50 \mu$ .

The individual taenite grains are quite complicated in their structure and composition, probably due to the combined effects of preterrestrial segregation and terrestrial corrosion. No kamacite is present except for minute, irregular 1-3  $\mu$  wide rims around some of the schreibersite inclusions. Normally, these kamacite rims are fully transformed into terrestrial oxides. Oxidation has also attacked the taenite matrix so that many of the essential structural elements are already visible on polished. unetched surfaces. Etching with 1-2% Nital or with Picral enhances the effects, sometimes blackening excessively and obscuring the details. The taenite is structureless except for the presence of densely spaced slipplanes. These are best observed along the grain boundaries where some plastic deformation and subsequent corrosion have contributed to their development.

Troilite is very common, both as grain boundary veins and as nodules in the interior. The veins, ranging from  $10 \,\mu$ to 2 cm in width, and the nodules, ranging from 50  $\mu$  to 5 mm across, cover 5-10% by area, averaging 8%. However, the grain boundary troilite may be easily overlooked because the smaller specimens are individual taenite grains broken along the grain boundaries. The troilite is heavily altered to at least two different sulfides, one of which appears to be pentlandite. In addition, free sulfur is present, often as beautiful, yellow incrustations on the more weathered specimens. Kvasha et al. (1969) confirmed the presence of sulfur by X-ray diffraction techniques. The best preserved troilite inclusions show the mineral to be monocrystalline with a few lenticular twins from slight plastic deformation and with a hardness of 265±15. Daubreelite is absent. The troilite has served everywhere as a substrate for precipitates of schreibersite which now covers it irregularly as 10-200  $\mu$  thick rims.

Schreibersite is further common as rosettes or skeleton crystals, typically 0.3-1.5 mm across and with a hardness of  $800\pm25$ . Schreibersite is also common as a generation of small, rhabdite-like bodies,  $10-50\,\mu$  across; but the

ubiquitous small rounded phosphides of Twin City are not present in Santa Catharina.

Accessory silicates, in the form of  $20-300 \,\mu$  rounded or angular bodies upon which phosphides have precipitated, occur irregularly. Some of these appear to be fayalite, as identified by Kvasha et al. (1969). Graphite was reported by Daubree (1877b) and Meunier (1884) but could not be confirmed in the present study.

There remains the problem concerning the number of taenite phases present. The application of various etching methods gave no unambiguous evidence of more than one phase in this study, and the data of Kvasha et al. seem to support this conclusion. I found, however, that the taenite phase is very heterogeneous, apparently erratic, in its hardness properties. A systematic examination revealed that the hardness is consistently high (HV 325±15) in the light-etching 100-500  $\mu$  wide zones around any schreibersite and troilite inclusion while it decreases to rather low values (HV 195±20) in the areas in between. As soon as visible oxidation is present the hardness increases to very high values. The range observed is 275-560, with an average of 450±40. The natural etching (corrosion) and the laboratory etching also suggest an advanced heterogeneity. The hard metal around the phosphides and sulfides is the last to be attacked, while the intermediate soft zones apparently are the less noble parts of the alloy. As may be seen from Figure 1523, the oxidation attack in its initial stages seems to create extremely flat lenses, typically 10 x 10 x 1  $\mu$  in size. These are arranged in the cubic planes of the taenite and one set happens to lie in the plane of the section in Figure 1524. The plates are spaced 5-20  $\mu$  apart but eventually coalesce when the corrosion progresses.

The reason for this peculiar form for internal oxidation is not known, but it may be assumed, from the gradients around phosphides and sulfides, that a microsegregation is responsible. Possible elements appear to be phosphorus and



Figure 1527. Santa Catharina (Brit. Mus. no. 52283). An oval silicate crystal (right of center) around which troilite (T) and schreibersite (S) have precipitated. The troilite is severely altered by weathering, showing light patches of pentlandite. Polished. Scale bar  $100 \mu$ .

copper; in addition, nickel may give rise to ordering effects and creating, ideally,  $Fe_3Ni$ . It should be possible, with electron microprobe techniques, to examine whether such a microsegregation has, in fact, occurred. If so, it would explain (i) the hardness gradients, (ii) the differential corrosion attacks and etching characteristics, and (iii) the advanced splitting into cubic fragments along oxidized zones. The two taenite phases of Lovering and Anderson (1965) might then be unoxidized and oxidized taenite, respectively. The surprising problem remains, however, that it seems to be the nickel-rich part which is the first to corrode.

Santa Catharina is an anomalous meteorite of high terrestrial age. It is very closely related to Twin City (30% Ni) and forms a natural extension of the meteorite spectrum to 36% Ni. It is polycrystalline with abundant troilite and schreibersite in the grain boundaries. Under the extended terrestrial exposure schreibersite has, in this case, proven to be the most stable mineral of the normal accessories while kamacite, taenite and troilite all show various degrees of deterioration. It is noteworthy that the immediate surroundings of schreibersite are not corroded except when a little kamacite is present. In other meteorites substantial rims of swathing kamacite — normally with a nickel gradient — are always present around the phosphides; and, therefore, the metal will corrode rapidly, and more rapidly if fractures are numerous along the inclusions.

It appears that the taenite is composed of only one phase which is uniformly oriented within each grain but which shows substantial heterogeneity with respect to P, Cu and, probably, Ni. Internal oxidation has altered the taenite to an unusual extent and has made an interpretation of the original structure and composition difficult. The unexpected and rapid, but systematic, fluctuations in the hardness level are interesting by suggesting two different forms of hardening mechanisms. One is order-hardening, probably to Fe<sub>3</sub>Ni, around the inclusions and in other low-nickel locations; the other is hardening by internal oxidation brought about by a long terrestrial exposure to terrestrial agents.

#### Specimens in the U.S. National Museum in Washington:

- 50 g mounted, metallic sections (no. 104,  $4 \times 3 \times 0.5$  cm and  $4 \times 3 \times 0.1$  cm)
- 276 g metallic nodule (no. 796, 5.5 x 4 x 4 cm). The label reads: The last of a lot of five tons of "nickel ore" shipped to Europe. John Allen. 1910.
- 15 g weathered, cubic fragment (no. 1133, 2 x 1.5 x 1 cm)
- 28 g metallic nodule (no. 1617, 2.5 x 1.5 x 1.5 x). Examined by S.H. Perry
- 341 g polycrystalline, metallic slice with limonite crust (no. 3043, 8 x 4 x 2 cm)
- 185 g limonite with sulfur incrustations (nos. 659 and 804, about 4 cm across)
- 6.80 kg limonitic mass with properties ranging from strongly magnetic to nonmagnetic (no. 1133, 30 x 15 x 12 cm)
- 3 kg extremely weathered fragments (nos. 877, 3042, 3367, 3368, 3369)

## Santa Fé. See Glorieta Mountain

# Santa Luzia, Goias, Brazil 16°6'S, 48°1'W; 850 m

Coarsest octahedrite, Ogg. Bandwidth  $5\pm2$  mm and 5 cm grains. Neumann bands. HV 175 $\pm8$ .

Group IIB. 6.60% Ni, 0.47% Co, 0.9% P, 48 ppm Ga, 110 ppm Ge, 0.010 ppm Ir.

#### HISTORY

According to Vidal (1931) the first vague information about this meteorite reached Rio de Janeiro's Mineralogical Museum in 1922, but because of the unsettled situation in the country, no action was taken. A fragment was exhibited in 1922 at the International Exposition in Rio which celebrated Brazil's centennial and it was awarded a bronze medal. The specimen was sold to the United States and is probably identical to the 4.5 kg individual which was acquired in 1925 by the Field Museum in Chicago. Six slices were cut from it in the Smithsonian Institution in 1926, so the remaining mass now weighs 2.5 kg (exchange of letters between Farrington and Merrill, Accession Number 87821; Horback & Olsen 1965: 291).

The main mass of 1,890 kg had evidently been well known to the local population for many years when it was excavated and transported to Rio de Janeiro's National Museum in 1928. The mass was lightly buried in micaceous schists in a small ravine, 20 km north-northwest of Santa Luzia (presently called Luziania) in the Federal District. Vidal (1931) gave a map and a colorful discription of the conveyance on a primitive carriage drawn by 18 oxen and assisted by 30 men. He quoted various incidents to indicate that the mass had fallen in June 1919, and this information is still retained in some catalogs (Horback & Olsen 1965: 291). However, the corrosion is so thorough that the terrestrial age must be counted in tens of thousands of years. Vidal provided two figures of the exterior.

In 1936 Ward's Natural Science Establishment imported two fragments of 18.4 and 9 kg which were acquired by the Smithsonian Institution (Nos. 1275 and 1219). They had been collected at the Upper Santa Maria River, 24 km from Santa Luzia, and had been found on the surface only one kilometer apart (Accession Numbers 143643 and 146466 in the Smithsonian Institution). This locality is only 2 or 3 km east of the main mass as may be seen by examining the original map sketch by Vidal (1931). Finally, Curvello (1950a) described a 1.64 kg individual which had been found on the surface only 100 m from the large mass. He gave a photograph of the exterior and two photomicrographs.

The shower has thus provided a large main mass and four small fragments scattered around it up to a few kilometers distance. Of course, more may be present but covered by soil or unreported.

Meen (1939) stated that six fragments were known, but this appears to be an error. He reexamined and reanalyzed the meteorite, and his two photomacrographs clearly show the very coarse, octahedral structure which is mixed with rounded patches of swathing kamacite. Perry (1944) also presented two photomacrographs, and Henderson (1965) reproduced and discussed two more photomacrographs of etched sections. Meen's, Perry's and Henderson's photographs all came from several parallel sections through the 9 kg mass (No. 1219) in the U.S. National Museum.

Vilcsek & Wänke (1963) measured the <sup>36</sup>Ar, <sup>36</sup>Cl and <sup>39</sup>Ar isotopes; and Chang & Wänke (1969) estimated, on basis of the low concentration of <sup>36</sup>Cl and <sup>10</sup>Be, that the terrestrial age was high – about 800,000 years, but with a high margin of uncertainty, however.

## COLLECTIONS

Rio de Janeiro, National Museum (1,890 kg main mass with 90 x 25 cm cut and polished face; slice; 1.6 kg individual), Washington (22.9 kg), Chicago (2,480 g half individual, 550 g slices), New York (1,525 g), Canberra (325 g), Tempe (280 g), Copenhagen (240 g), Calcutta (232 g), Moscow (140 g), Paris (54 g).

## DESCRIPTION

The 1,890 kg mass, as examined by the author in 1973, is an irregular flat disk, pointed at both ends, and measuring about 120 x 80 x 50 cm. A rough, deep-etched cut exposes a 80 x 20 cm surface parallel to the long axis and perpendicular to the topside. The mass is boldly sculptured, displaying several basins and pits. On the topside one basin measures 45 x 30 cm with a depth of 20 cm, another is 25 x 16 cm with a depth of 10 cm. A third triangular, imperfect basin, 45 x 20 cm across and 9 cm deep, is itself divided into five smaller pits. In one place is is clearly observed how a troilite vein has been partially ablated away, leaving a hole 3 cm across.

It appears that the sculpture on the topside and the sides is almost exclusively due to ablative sculpturing during atmospheric flight, and it is estimated that less than 2 mm has been lost to weathering. The buried underside has, however, been more exposed to corrosion. There are heavy layers of oxide, which slowly crumble and become detached; here, probably more than 5 mm has been lost on the average.

Hammering and chiseling marks are seen in many places, and three rough fractures along the edge indicate where fragments have been violently broken away. However, the mass has not been exposed to artificial reheating.

There are two small individuals in the U.S. National Museum. Before cutting they weighed 18.4 kg (No. 1275) and 9 kg (No. 1219) and had the average dimensions 28 x

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16 x 11 and 20 x 14 x 10 cm, respectively. Both masses are irregularly rounded and covered with a crust of terrestrial oxides that reaches a thickness of 6 mm in places. All regmaglypts, fusion crust and heat-affected  $\alpha_2$  zones are lost by weathering. Corrosion penetrates along the grain boundaries and particularly follows the phosphides. Limonitic veins, 0.1-1 mm thick, are present in the center of the masses, and the near-surface troilite-schreibersite nodules are severely altered. Some corrosion is also present along the near-surface Neumann bands.

Locally, a few fragments have been chiseled from the specimens in recent times, but the two small masses themselves were not artificially detached from the large main mass but must have separated from it in the atmosphere and fallen independently.

Etched sections display a beautiful mixture of a very coarse Widmanstätten structure and of apparently equiaxial kamacite grains. The kamacite lamellae are very short and bulky ( $\frac{L}{W} \sim 4$ ) and have a width of 5±2 mm. The oriented lamellar structure is not pronounced because significant amounts of swathing kamacite had developed around numerous large schreibersite-metal-troilite eutectics before the Widmanstätten structure could grow. The eutectics, including the swathing kamacite rims, cover – on the average – 30% of the available sections. The interfaces between the swathing and the lamellar kamacite areas are ragged because some late grain boundary adjustment has taken place. It is always the swathing kamacite structure.

The kamacite has well developed subboundaries decorated with  $1-2 \mu$  thick rhabdites. Neumann bands are common, some of them being decorated by rows of  $1-2 \mu$ 



Figure 1528. Santa Luzia (U.S.N.M. no. 1618). A coarsest octahedrite of group IIB. In center, a troilite pocket and associated rosetta-schreibersite. Deep-etched. Scale bar 30 mm. S.I. neg, 32948A. See also Figure 199.

ANTA LUZ	A - SELECTE	ED CHEMICAL	ANALYSES
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	р	ercentage	e					ppm				
References	Ni	Co	Р	С	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1969	6.39								47.9	110	0.010	
Lewis & Moore 1971	6.82	0.47	0.44	40								

thick rhabdites. The hardness is  $175\pm8$ , decreasing to  $150\pm5$  in the nickel- and phosphorus-depleted  $\alpha$ -zones around schreibersite.

Taenite and plessite cover less than 1% by area, mostly situated in the grain boundaries but occasionally completely embedded within one uniformly oriented swathing kamacite grain. The comb plessite attains sizes of 3 x 2 mm and it exhibits pearlitic, spheroidized and martensitic areas. The pearlite (HV 235±15) has parallel narrow taenite lamellae, 0.5-1  $\mu$  wide. The spheroidized areas (HV 200±20) have taenite spherules, 1-20  $\mu$  in diameter. The martensitic areas (HV 440±50) exhibit both acicular and platy martensite and in places are annealed to fine-grained duplex structures.

Schreibersite is the essential component of the eutectics where it forms 1-5 mm wide, winding ribbons with an occasional crystallographic facet. Its hardness is  $925\pm25$ . Chromite is locally present as 0.5-1 mm wide euhedral cubes with rounded faces. Schreibersite is further common as  $20-200 \mu$  wide grain boundary veinlets. Rhabdites are very common, perhaps mainly as  $0.5-2 \mu$  thick prisms in the kamacite interior. The Neumann bands are narrow,  $0.5-1 \mu$ , in the rhabdite-loaded areas but are as wide as  $10 \mu$  in the rhabdite-free zones near schreibersite.

Troilite forms long subparallel stringers and irregular plates through the whole mass. The exposed surface of the main mass in Rio de Janeiro (Vidal 1931: 20) clearly shows that the sulfide is oriented parallel to the topside and underside of the main mass, thus suggesting a mild hot working with compression and some shearing. The texture suggests that the mass was deformed during slight movements of the overburden on the parent asteroid. Santa Luzia thus appears to be a single "raisin" in the Urey raisin bread model. Due to shock of a much later date, the troilite is either deformed, with lenticular twins, or is completely melted and resolidified to 1-10  $\mu$  grain aggregates. The troilite melts attain sizes of 20 mm in diameter and exhibit ragged edges against the partly dissolved metal. The adjacent schreibersite is shattered and partially dispersed in the troilite as fragments, 1-100  $\mu$  across. Daubreelite does not appear to be present.

Not only is the troilite elongated parallel to the present exterior surfaces, but the schreibersite-metal eutectics associated with it also appear to have formed parallel cylinders 10-40 mm in diameter. Later, swathing kamacite has grown around these cylinders in the solid state to form concentric shells, 5-15 mm thick. Troilite forms the central part of the cylinders; but, since it pinches and swells irregularly, it may or may not be present in a given section perpendicular to the cylinders. There is a very strong indication that the inner cylinders were molten mixtures of sulfide and phosphorus-rich liquids at a temperature of about  $1000^{\circ} \text{ C} - \text{a}$  temperature at which most other irons were completely solidified, except for occasional troilite nodules.

A planimetric examination of several sections indicates that schreibersite covers 5-6% by area, 90% of it visibly associated with the eutectic structures. The remaining 10% is either late grain or subgrain boundary precipitates or is small skeleton crystals which may be part of eutectics below or above the sectioned surface. The average, 5.5% P by area or volume, corresponds to 0.76% P by weight; if we add 0.14% P to account for the microscopic rhabdites and phosphorus in solid solution, we arrive at 0.9 weight % P as a bulk value for the whole mass. Planimetry further shows that schreibersite constitutes 30-35% of the eutectic areas. Whether or not troilite is present, schreibersite covers this amount, so the troilite appears to be a rather passive constituent which does not form eutectics.

The planimetry reveals that the bulk phosphorus content of a schreibersite-rich iron meteorite may be grossly underestimated by normal, chemical-analystical methods. It appears that low-melting, eutectic pockets of phosphorus-rich liquid may occur in irons with a bulk composition of 6.6% Ni, 0.47% Co and 0.9 P. The residual liquid, which now exhibits by area 32% schreibersite with 15.4% P, must have had a composition with about 0.32 x  $\frac{7.0}{7.8}$  x 0.154 = 4.5% P! This is a surprisingly low P-value for a rest melt in the ternary Fe-Ni-P system. From diagrams published by Buchwald (1966: 10) and Doan & Goldstein (1970), one would rather estimate the residual liquid to have had about 12% P and to have formed a schreibersitemetal intergrowth in the ratio 2:1, instead of, as observed, 1:2. It is not clear where the discrepancy lies; the quaternary Fe-Ni-P-S system, unfortunately, is little known.

While the quantitative interpretation of the complex schreibersite-troilite structures is somewhat uncertain, there is little doubt that they represent long, platelike or cylindrical zones through the meteorite and that they were the last components to solidify. They represent a rare case of orientation in an iron meteorite that must date back to the environment on the parent asteroidal body. Santa Rosa, Carbo, Bendego, Cape York and a few others apparently represent similar cases; however, the phosphorus concentration in these was too low for any significant amount of schreibersite to join with the troilite.

Structurally, Santa Luzia closely resembles Silver Bell. In a recent paper Wasson (1969) showed that also their trace-element composition is virtually identical. Santa Luzia is also related to Sikhote-Alin and other irons in group IIB.

Specimens in the U.S. National Museum in Washington:

- 297 g part slice (no. 772, 8 x 4.5 x 1 cm; from the 4 1/2 kg Chicago specimen)
- 5.53 kg half mass (no. 1219, 13 x 14 x 8 cm)
- g two slices from above (no. 1219, 14 x 9 x 0.6 cm each)
- 288 g polished slice from no. 1219 (no. 1618, 13 x 8 x 0.5 cm) 160 kg individual with 15 x 0 cm out (no. 1275, 12 x 28 x
- 16.0 kg individual with 15 x 9 cm cut (no. 1275, 12 x 28 x 11 cm)